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Extending Quasi-static Range Finitely Conducting Earth Image Theory Techniques to Other Ranges

Peter R. Bannister
Submarine Electromagnetic
Systems Department

7 July 1977

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PREFACE

The work described in this report was performed under NUSC Project No. A-590-07, "Project SEAFARER ELF Propagation Studies," Principal Investigator, P. R. Bannister (Code 341); Navy Program Element No. 11401 and Project No. X0792, Naval Electronic Systems Command, Special Communications Project Office, CAPT C. D. Pollak (Code PME-117), Program Manager, ELF Communications Division, Dr. B. Kruger (Code PME 117-21), Director.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number):

By a simple extension to the Wait and Spies quasi-static range finitely conducting earth image theory approximation, it is shown that finitely conducting earth image theory techniques can also be applied to the nearfield and farfield ranges. Both vertical magnetic dipole (VMD) and long horizontal line sources are considered.

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INTRODUCTION

During the past few years, finitely conducting earth image theory techniques have proved quite useful in determining quasi-static range field component expressions (of simple form) for antennas located near the earth's surface -- for both single layered and multilayered earths.[1-6] The quasi-static range is defined as that range where the measurement distance is much less than a free-space wavelength.

Physically, the essence of the finitely conducting earth image theory technique is to replace the finitely conducting earth by a perfectly conducting earth located at the (complex) depth $d/2$, where $d = 2/\gamma = \delta(1-i)$, γ is the propagation constant in the earth, and δ is the earth skin depth. Analytically, this corresponds to replacing the algebraic "reflection coefficient" $(u-\lambda)/(u+\lambda)$ in the exact integral expressions by exponent $(-\lambda d)$, where λ is the variable of integration. For antennas located at or above the earth's surface, this approximation is valid throughout the quasi-static range.[1,6]

It is the purpose of this report to show that finitely conducting earth image theory techniques are not limited to the quasi-static range alone. We will demonstrate that they can be utilized at <u>any</u> range from the source.

We will consider two sources: (1) an infinitely long cable (i.e., a long horizontal line source), located at height h ($h > 0$) with respect to a Cartesian coordinate system (x,y,z), carrying a constant current I in the positive x direction, and (2) a vertical magnetic dipole (VMD), located at height h ($h > 0$) with respect to a cylindrical coordinate system (ρ, ϕ, z), carrying a constant current I, and whose axis is located in the z direction. The homogeneous earth (of conductivity σ and dielectric constant ε) occupies the lower half-space ($z < 0$), while the air occupies the upper half-space ($z > 0$). The magnetic permeability of the earth is assumed to equal μ_0, the permeability of free space. Meter-kilogram-second (mks) units are employed and a suppressed time factor of $\exp(i\omega t)$ is assumed.

LONG HORIZONTAL LINE SOURCE

For an infinitely long cable, located at height h with respect to a Cartesian coordinate system and carrying a constant current I in the

positive x direction, the resulting electric field in air is given exactly by[7]

$$E_x = -\frac{i\omega\mu_o I}{2\pi}\int_o^\infty \frac{1}{u_o}\left[e^{-u_o|z-h|} - \left(\frac{u-u_o}{u+u_o}\right)\right.$$

$$\left.\cdot\ e^{-u_o(z+h)}\right]\cos\lambda y d\lambda\ , \tag{1}$$

where

$u_o = (\lambda^2 + \gamma_o^2)^{1/2}$

$u = (\lambda^2 + \gamma^2)^{1/2}$

$\gamma_o = i\omega(\mu_o\varepsilon_o)^{1/2}$

$\gamma = \left[i\omega\mu_o(\sigma + i\omega\varepsilon)\right]^{1/2}$, and

ε_o is the dielectric constant of the upper half-space.

Now for the quasi-static range ($\gamma_o \sim 0$), Wait and Spies[3] have shown that

$$\frac{u-u_o}{u+u_o} \sim \frac{u-\lambda}{u+\lambda} \sim e^{-\lambda d}\ . \tag{2}$$

Substitution of equation (2) into equation (1) results in

$$E_x \sim -\frac{i\omega\mu_o I}{2\pi}\int_o^\infty \frac{1}{\lambda}\left[e^{-\lambda|z-h|} - e^{-\lambda(d+z+h)}\right]\cos\lambda y d\lambda\ . \tag{3}$$

These integrals may be readily evaluated[8] to yield

$$E_x \sim -\frac{i\omega\mu_o I}{2\pi}\,\ell n\left(\frac{R_i}{R_o}\right), \tag{4}$$

and

$$e^{-\gamma_o R_i} \sim e^{-\gamma_o R_1}\left\{1 - \gamma_o d\left(\sin\psi + \frac{d\cos^2\psi_1}{2R_1}\right)\right\}, \tag{14}$$

where $\sin\psi_1 = (z+h)/R_1$ and $\cos\psi_1 = \rho/R_1$. Thus,

$$E_x \sim -\frac{i\omega\mu_o I}{2\pi}\sqrt{\frac{\pi}{2}}\left\{\frac{e^{-\gamma_o R_o}}{\sqrt{\gamma_o R_o}}\right.$$

$$\left. - \left[1 - \gamma_o d\left(\sin\psi_1 + \frac{d\cos^2\psi_1}{2R_1}\right)\right]\frac{e^{-\gamma_o R_1}}{\sqrt{\gamma_o R_1}}\right\}. \tag{15}$$

When $|\gamma^2| \gg |\gamma_o^2|$, the reflection coefficient for horizontal polarization ($\Gamma_\perp$) is equal to

$$\Gamma_\perp \sim \frac{\sin\psi_1 - \gamma/\gamma_o}{\sin\psi_1 + \gamma/\gamma_o} \sim -1 + \gamma_o d\sin\psi_1. \tag{16}$$

Therefore, E_x may be expressed as

$$E_x \sim -\frac{i\omega\mu_o I}{2\pi}\sqrt{\frac{\pi}{2}}\left[\frac{e^{-\gamma_o R_o}}{\sqrt{\gamma_o R_o}} + \left(\Gamma_\perp - \frac{\cos^2\psi}{\gamma R_1}\right)\frac{e^{-\gamma_o R_1}}{\sqrt{\gamma_o R_1}}\right]. \tag{17}$$

When $|\gamma_o h| \gg 1$ and $h \gg z$, and when $z = h = 0$, equation (17) reduces to the previously derived farfield results of Wait[7] (Wait's equations (54) and (65)).

Since equation (10) reduces to known results when (a) $|\gamma_o R_i| \ll 1$, (b) $|\gamma_o R_i| \gg 1$, and (c) σ approaches infinity, it will be valid at any range from the source.

The magnetic fields produced by an infinitely long cable (which reduce to equations (6) and (7) when $|\gamma_o R_i| \ll 1$, and which will also be valid at any range from the source) may easily be determined from equations (5) and (10). Thus, we see that

$$H_y \approx -\frac{I}{2\pi}\left[\frac{\gamma_o(z-h)}{R_o}K_1(\gamma_o R_o) - \frac{\gamma_o(d+z+h)}{R_i}K_1(\gamma_o R_i)\right] \tag{18}$$

and

$$H_x \approx \frac{I}{2\pi}\left[\frac{\gamma_o y}{R_o}K_1(\gamma_o R_o) - \frac{\gamma_o y}{R_i}K_1(\gamma_o R_i)\right] , \tag{19}$$

where K_1 is the modified Bessel function of the second kind, order one.

VERTICAL MAGNETIC DIPOLE SOURCE

The VMD, of infinitesimal area A, is located at height h with respect to a cylindrical coordinate system. It carries a constant current I and its axis is located in the z direction. When h and z are ≥ 0, the exact Sommerfeld integral expression for the VMD Hertz potential is

$$\Pi_z = \frac{IA}{4\pi}\left[\frac{e^{-\gamma_o R_o}}{R_o} - \int_0^\infty \frac{\lambda}{u_o}\left(\frac{u-u_o}{u+u_o}\right)e^{-u_o(z+h)} J_o(\lambda\rho)d\lambda\right]. \tag{20}$$

The fields in air are related to the Hertz potential by

$$E_\phi = i\omega\mu_o \frac{\partial\Pi_z}{\partial\rho} \; ; \; H_z = \left(-\gamma_o{}^2 + \frac{\partial^2}{\partial z^2}\right)\Pi_z \; ; \; H_\rho = \frac{\partial^2\Pi_z}{\partial\rho\partial z} . \tag{21}$$

Substituting equation (8) into equation (20) and evaluating the integral[8] yields

$$\Pi_z \approx \frac{IA}{4\Pi}\left(\frac{e^{-\gamma_o R_o}}{R_o} - \frac{e^{-\gamma_o R_i}}{R_i}\right) , \tag{22}$$

where R_o^2 is now defined to be equal to $\rho^2 + (z-h)^2$ and $R_i{}^2$ is now defined to be equal to $\rho^2 + (d+z+h)^2$. From equations (21) and (22) we see that

$$E_\phi \sim -\frac{i\omega\mu_o IA}{4\pi}\left[\frac{\rho}{R_o^{\,3}}(1+\gamma_o R_o)e^{-\gamma_o R_o} - \frac{\rho}{R_i^{\,3}}(1+\gamma_o R_i)e^{-\gamma_o R_i}\right] \tag{23}$$

$$H_\rho \sim \frac{IA}{4\pi}\left\{\frac{\rho(z-h)e^{-\gamma_o R_o}}{R_o^{\,5}}\left[3+3\gamma_o R_o+\gamma_o^{\,2}R_o^{\,2}\right]\right.$$

$$\left.-\frac{\rho(d+z+h)e^{-\gamma_o R_i}}{R_i^{\,5}}\left[3+3\gamma_o R_i+\gamma_o^{\,2}R_i^{\,2}\right]\right\} \tag{24}$$

and

$$H_z \sim -\frac{IA}{4\pi}\left\{\frac{e^{-\gamma_o R_o}}{R_o^{\,3}}\left[\left(1-\frac{3(z-h)^2}{R_o^{\,2}}\right)\left(1+\gamma_o R_o\right)+\gamma_o^{\,2}\rho^2\right]\right.$$

$$\left.-\frac{e^{-\gamma_o R_i}}{R_i^{\,3}}\left[\left(1-\frac{3(d+z+h)^2}{R_i^{\,2}}\right)\left(1+\gamma_o R_i\right)+\gamma_o^{\,2}\rho^2\right]\right\}. \tag{25}$$

When $|\gamma_o R_i| << 1$, equations (22) through (25) reduce to

$$\Pi_z \sim \frac{IA}{4\pi}\left(\frac{1}{R_o}-\frac{1}{R_i}\right) \tag{26}$$

$$E_\phi \sim -\frac{i\omega\mu_o IA}{4\pi}(\rho)\left(\frac{1}{R_o^{\,3}}-\frac{1}{R_i^{\,3}}\right) \tag{27}$$

$$H_\rho \sim \frac{3IA}{4\pi}(\rho)\left[\frac{(z-h)}{R_o^{\,5}}-\frac{(d+z+h)}{R_i^{\,5}}\right] \tag{28}$$

and

$$H_z \sim -\frac{IA}{4\pi}\left\{\frac{1}{R_o^{\,3}}\left[1-\frac{3(z-h)^2}{R_o^{\,2}}\right]-\frac{1}{R_i^{\,3}}\left[1-\frac{3(d+z+h)^2}{R_i^{\,2}}\right]\right\}, \tag{29}$$

which are identical to Bannister's[1] previously derived quasi-static range finitely conducting earth image theory results.

After some manipulation, it can be shown that when $|\gamma_o R_i| >> 1$ and $|\gamma^2| >> |\gamma_o{}^2|$, equations (23) through (25) reduce to the farfield results of Norton.[9]

When $z = h = 0$, the exact solution for the VMD E_ϕ and H_z components are[10]

$$E_\phi \sim -\frac{i\omega\mu_o IA}{2\pi(\gamma^2-\gamma_o{}^2)\rho^4}\left[(3+3\gamma_o\rho+\gamma_o{}^2\rho^2)e^{-\gamma_o\rho}\right.$$

$$\left.-(3+3\gamma\rho+\gamma^2\rho^2)e^{-\gamma\rho}\right] \tag{30}$$

and

$$H_z \sim -\frac{IA}{2\pi(\gamma^2-\gamma_o{}^2)\rho^5}\left[\left(9+9\gamma_o\rho+4\gamma_o{}^2\rho^2+\gamma_o{}^3\rho^3\right)e^{-\gamma_o\rho}\right.$$

$$\left.-(9+9\gamma\rho+4\gamma^2\rho^2+\gamma^3\rho^3)e^{-\gamma\rho}\right]. \tag{31}$$

These expressions are valid at all distances from the source.

If $\rho >> \delta$ and $|\gamma^2| >> |\gamma_o{}^2|$, equations (23) and (25) reduce to

$$E_\phi \sim -\frac{i\omega\mu_o IA}{2\pi\gamma^2\rho^4}\left(3+3\gamma_o\rho+\gamma_o{}^2\rho^2\right)e^{-\gamma_o\rho} \tag{32}$$

and

$$H_z \sim -\frac{IA}{2\pi\gamma^2\rho^5}\left(9 + 9\gamma_o\rho + 4\gamma_o^2\rho^2 + \gamma_o^3\rho^3\right)e^{-\gamma_o\rho} , \qquad (33)$$

which are identical to equations (30) and (31) when $|\gamma\rho| >> 1$ (i.e., $\rho >> \delta$) and $|\gamma^2| >> |\gamma_o^2|$. Thus, equations (23) through (25) will be valid at any range from the source.

CONCLUSION

In this report we have derived field component expressions produced by vertical magnetic dipole and long horizontal line sources which are valid at any range from the source. These results have been accomplished by a simple extension to the Wait and Spies quasi-static range finitely conducting earth image theory approximation.

The results presented in this report can easily be extended to a multilayered earth simply by letting the (complex) image depth d/2 equal (δ/2) (1-i) Q, where Q is the familar plane wave correction factor employed to account for the presence of stratification in the earth.[6,7]

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